

CELSS Research and Development Program

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A Controlled Ecological Life Support System (CELSS) will be a regenerative system which incorporates biological, physical and chemical processes to support humans in extra-terrestrial environments. The key processes in such a system are photosynthesis, whereby green plants utilize light energy to produce food and oxygen while removing carbon dioxide from the atmosphere, and transpiration, the evaporation of water from stomata. Development of a CELSS requires identification of the critical requirements that will allow the system to operate with stability and efficiency. Identifying and meeting those requirements will be accomplished through scientific experimentation and technology development on the ground followed by space flight testing to validate microgravity and reduced gravity adaptability of the system.

NASA's Ames Research Center (ARC) has responsibility for three major CELSS program elements:

- 1) Research and Development (R & D)
- 2) System Integration and Control
- 3) Space Flight Experiments

The Research and Development Program includes evaluation of new ideas and development of advanced principles and technologies in the areas of biomass production, waste processing, water purification, air revitalization and food processing. System Integration and Control involves identification of how the individual component processors of a CELSS can be linked and managed to operate in concert as a system. Both the R&D

and System Integration and Control program elements rely on the long-term involvement and interaction of NASA and university scientists and engineers. The Space Flight Program currently is planning for the CELSS test and demonstration hardware to be included as part of Space Station Freedom.

RESEARCH AND DEVELOPMENT

Approach. The CELSS program goal is development of a life support system based upon combining biological and physical/chemical processes capable of recycling the food, air and water needed to support long-term missions with humans in space. Efficiency of the system will be determined based on the ability of the system to recycle mass, thus reducing or eliminating resupply, and the production of human usable products (food, water, O₂, and CO₂ removal) per unit input to the system. The inputs considered important to CELSS system efficiency are volume, energy, time and mass. While these inputs are clearly important, the relative importance of each is subject to change based on mission scenario. A CELSS or individual component technologies may have application in a range of mission scenarios including lunar and planetary bases, space stations and planetary transit.

CELSS research and development has concentrated on characterizing operation of the potential component technologies. For the plant system, the approach has been to identify the flexibility and response time for the food, water and oxygen production, and carbon dioxide consumption pro-

cesses. To deal with the possibility of changing input limitations, depending on mission scenario, response surfaces are being developed to characterize system performance as a function of inputs. These response surfaces will be utilized to develop potential system designs for specific mission scenarios. Input limitations can be identified for each mission and the response surfaces will feed system trade studies to determine product priority and optimum system design, a process referred to as constrained optimization.

Plant Research. The goal of the R&D program in plant/crop physiology is to characterize the ability of a plant-based system to provide food, O₂, purified water and remove CO₂ from the closed

environments of spacecraft for the purpose of life support. The emphasis of plant research to date has been placed on food production with particular attention to methods of reducing the crop area (volume) required to sustain a human, compared with the area presently required in terrestrial agriculture. The discipline of crop physiology has been invoked with the aim of understanding the dynamics of yield development. Crop physiology is related to ecology but without the competition of diverse species and follows a biographical approach to crop development, with emphasis on the critical stages in yield determination and controlling factors for each stage. Research and development includes the conduct of basic research at universi-



Figure 1. Controlled environment plant growth chambers provide control of radiation quality and quantity, carbon dioxide level, humidity, hydroponic nutrient solution. (Photo: NASA Ames Research Center)

ties and at Ames, using controlled environment plant growth chambers, including control of radiation quality and quantity, CO₂ levels, humidity, and hydroponic nutrient solution delivery (Figure 1), and the conduct of closed systems research and study utilizing the Crop Growth Research Chamber (CGRC) at Ames (Figure 2).

The basic research program includes cooperative agreements with university investigators and performance of research at Ames. The goal of the basic research program is to characterize the performance of crop plants and identify optimum environments allowing full expression of the genetic potential (including nontraditional systems of algae, bacteria, and yeast). Studies related to plant purification of concentrated liquid waste streams, as well as, polishing of more dilute waste streams such as hygiene and grey water are also pursued. Nutrients derived from waste streams (recycled) via waste processing will be evaluated and acceptability for plant growth determined.

Crops included in the research were selected for specific purposes. Wheat was selected as a

carbohydrate source with the canopy architecture of a grass, potato as an alternative carbohydrate source with a broadleaf canopy architecture, soybean because of the relatively equal proportions of carbohydrate, proteins, and fats, and lettuce was selected as a model photosynthetic system which is not complicated by monocarpic senescence. For each of the crops selected there already exists a large body of knowledge concerning genetics, productivity and response to the environment. Building on present knowledge, environmental manipulation has been practiced in attempts to achieve maximal production in these model crop systems. Light quality, quantity, and periodicity, temperature, nutrient solution delivery and quality, CO₂ concentration in the atmosphere, plant density, and other factors have been altered from traditional agricultural systems to increase productivity.

Accomplishments over the past several years include: exceeding world record field yields, reducing seeding to harvest cycles by more than 50%, improving light utilization efficiency by a factor of 4, proving feasibility of a crop based CELSS where

Parameter	Control Range	Accuracy
<i>Atmospheric Environment</i>		
Air Temperature	5-40°C	±1°C
Air Pressure	+ 15 mm H ₂ O(gage)	± 5 mm
H ₂ O(gage)		
Relative Humidity	35-90%	± 2%
Air Composition		
Nitrogen	75-95%	± 5%
Oxygen	5-25%	± 5%
Carbon Dioxide	25-5000 µmol mol ⁻¹	± 0.2%
Air Flow Rate	0.1-1.0 m s ⁻¹	± 0.1 m s ⁻¹
Photosynthetic Photon Flux	0-3000 µmol m ⁻² s ⁻¹	± 2%
<i>Hydroponic Environment</i>		
Temperature	5-40°C	± 1°C
pH	4.8-8.0	± 0.2 units
Conductivity	0.5-5.0 dS m ⁻¹	± 0.5 dS m ⁻¹
Oxygen Concentration	5-20 µmol mol ⁻¹	± 2%

Table 1. CGRC Science Requirements for Environmental Control.

10 to 15 m² of crop can provide the food energy required to sustain one person and produce oxygen and water in great excess of their needs.

Current efforts are in areas of improving efficiency of the cropping system even more, evaluation of potential for phasic manipulation of plant development to further reduce the time to harvest, evaluation and selection of "new" CELSS crop plants appropriate for a balanced human diet, manipulation of plant metabolism to reduce production of inedible biomass, and increase harvest index (edible biomass / total biomass).

Waste Processing. The major objective of the waste processing R&D program is to evaluate, develop and select candidate physical, chemical

and biological waste treatment technologies for processing and recycling wastes. The evaluation and selection process includes pre- and post-treatment technologies that are needed for waste processing. Subsystem evaluations include material and energy balances and development and validation of models. Research in technology development is conducted at Ames and in cooperation with university investigators as appropriate.

Past work has specifically emphasized characterization of waste stream quality and quantity in present Space Shuttle missions and proposed missions including CELSS. Potential methods for processing individual waste streams to usable forms are identified by coupling stream constituents with

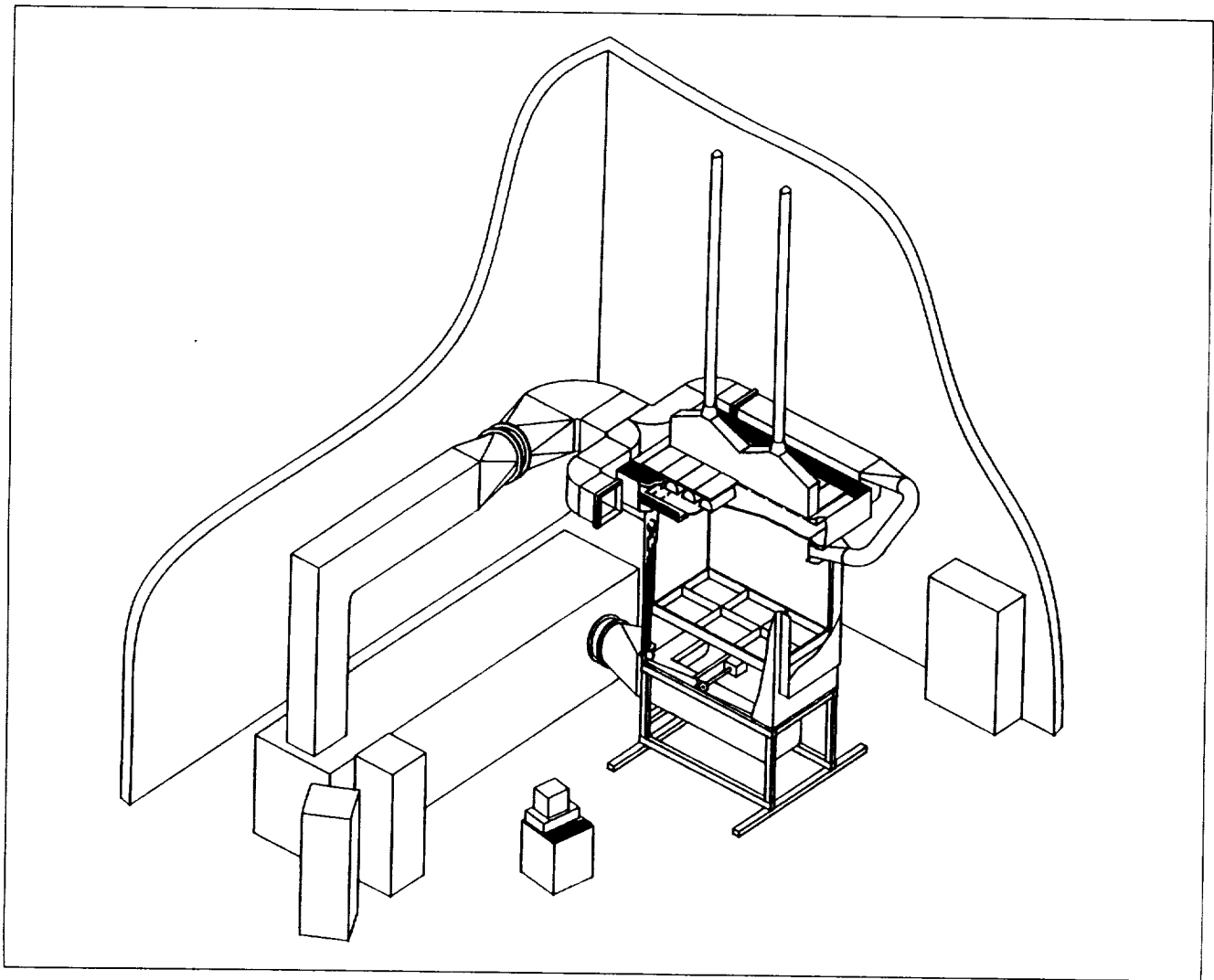


Figure 2. Anticipated physical appearance of the Grop Growth Research Chamber with chamber cut away to chamber interior with view of root zone compartments of the hydroponic system. (NASA Ames Research Center)

a desirable process product. Significant effort has been spent on developing oxidation processes, in particular wet oxidation and super-critical water oxidation. The products of these oxidation treatments, water, CO₂ and inorganic salts, are all desirable in a plant based life support system. Commercially available technologies such as incineration are also being evaluated.

Closed Systems Studies. The Crop Growth Research Chamber (CGRC) is used for the study of plant growth and development under stringently controlled environments isolated from the external environment (closed) and is designed for the growth of a community of crop plants (Table 1). The CGRC is the individual unit where various combinations of environmental factors can be selected and the influence on biomass, food and water production and O₂/CO₂ exchange of crop plants are investigated (Figure 3). Several Crop Growth Research Chambers and laboratory support equipment provide the core of a closed systems plant

research facility. This facility will be utilized for research, technical studies (development and evaluation of technology), system control, system modeling (development and validation), and system operation. Biomass produced in the CGRC and other controlled environment facilities at Ames will be made available for testing in the waste processing systems.

The closed systems plant research facility will supply a defined operation scenario for the plant component of the integrated experimental regenerative system and operate concurrent with integrated system evaluation.

System Control and Integration

Operation and control of a stable system is essential for development of a reliable life support system. The crop growth unit is only one portion of a CELSS but the crop plants function as several unique component processors. Carbon dioxide is removed from the atmosphere while oxygen is

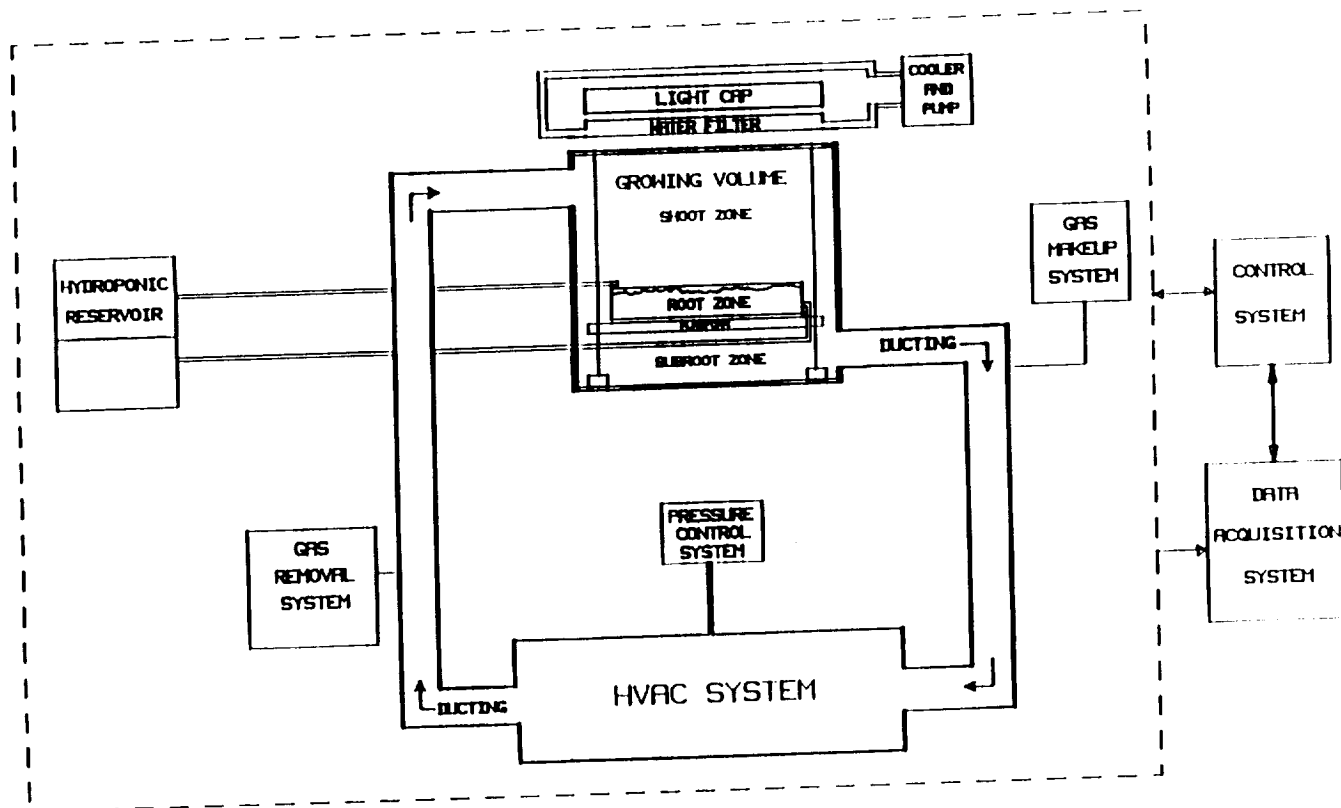


Figure 3. Block diagram of component subsystems and physical zones of the Crop Growth Research Chamber. (NASA Ames Research Center)

introduced through photosynthesis. Plant transpired water has been filtered through uptake by the root and incorporation of solutes into tissue before being evaporated from the interior of stomata of the leaves to the atmosphere. Transpiration rate can be manipulated over a wide range by environmental conditions. Carbon dioxide utilization and oxygen and water production are dynamic systems with short response times and the rate at which these processes operate can be varied as needs for a particular product vary. Of course food is being produced by the plants at the same time; the response time for expression of perturbations in the food production process is much greater than that observed for the other plants processes.

Edible plant yield is the integration of development during several unique phases between germination and harvest. Understanding the dynamics of yield development, i.e. having knowledge of crop responses to environmental manipulation during yield critical phases, is essential to predicting sys-

tem performance. Carbon dioxide uptake, and oxygen, water, and food can all be considered as products of the plant component of a CELSS. Information required for trade-off analysis to determine the short- and long-term gains and losses resulting from environmental manipulation during the life cycle of a crop as required for the desired plant product will be provided.

Future interface with candidate unit processors on a laboratory scale will be possible. As candidate processes are developed for such operations as waste processing, oxygen removal and storage, nutrient recycle, and harvest and food processing, laboratory scale prototype units could be interfaced with the CGRC. Performance of these processors and requirements for interface with a crop growing unit could be evaluated.

Integrated regenerative systems evaluation involves selection, integration and operation of technologies and subsystems developed in plant production and waste processing R&D programs

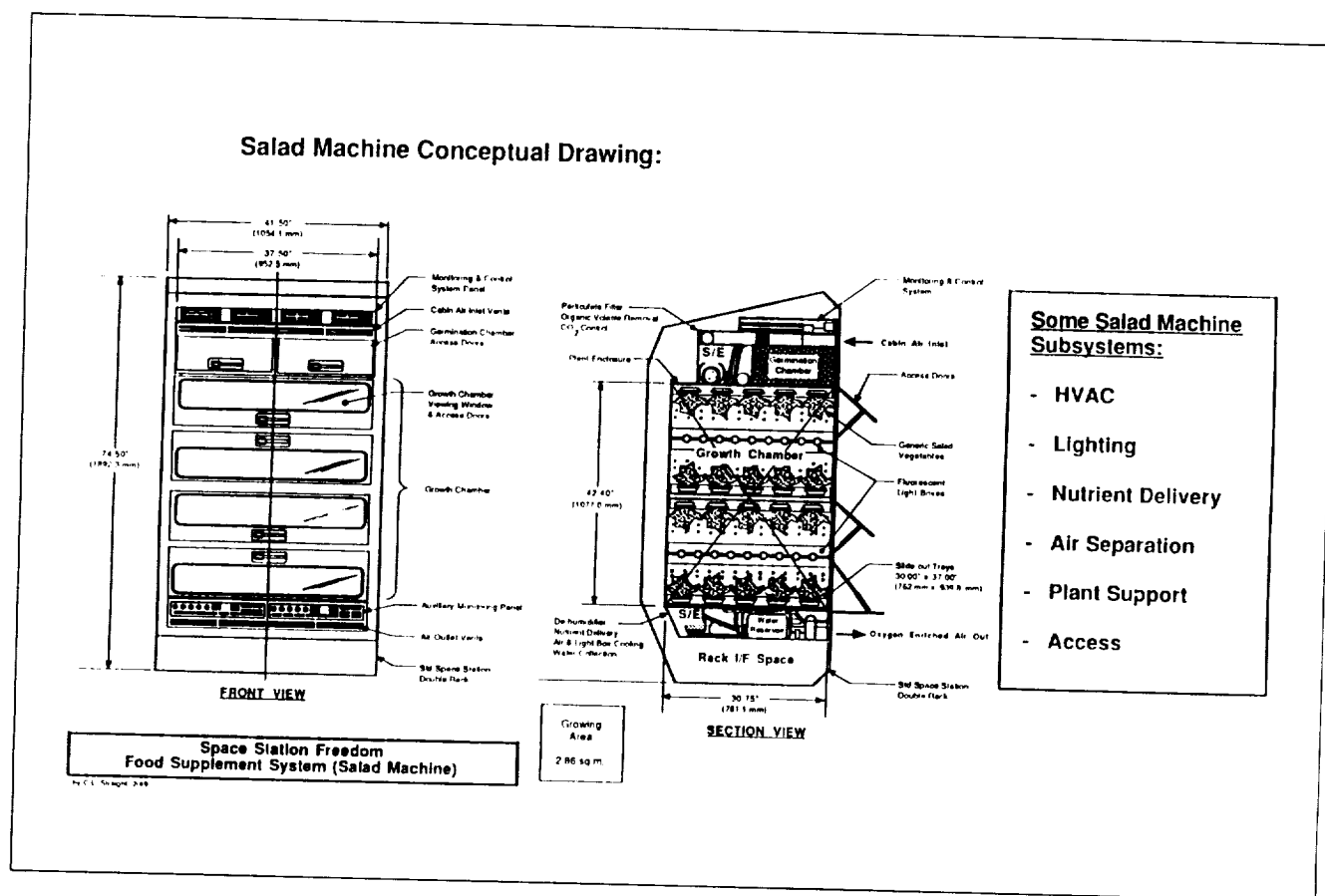


Figure 4. Conceptual drawing of CELSS Salad Machine. (NASA Ames Research Center)

in concert as part of an operational regenerative system. A CGRC (or modified CGRC) will be utilized as the plant growth component of the experimental regenerative system. Waste management subsystems will be sequentially added to the CGRC. Interface requirements for physical, chemical and biological subsystems will be defined. Technical development for automation of functions such as planting, harvest, food processing and conditioning treatment of waste streams before or after processing will be accommodated. CELSS system models and control strategies will be tested for the first time in real closed loop systems, mass and energy balances will be determined and the dynamics of the CELSS system defined for various input limitations (including those imposed by mission scenarios). The ultimate goal of integrated systems evaluation will be design specifications for the crew scale (possibly human rated) life support system testing.

Flight Test and Experimentation

The major emphasis for space flight has been planning for the CELSS Test Facility and the Salad Machine, both to be operated on Space Station Freedom. The CELSS Test Facility (CTF) is part of the NASA Life Sciences Space Biology Initiative. Capability for production of several generations of plant communities and the study of microgravity effects on plant performance is the goal of the CTF. The Salad Machine is being designed to regularly supply crew members of Space Station with salads (Figure 4). Precursor missions on shuttle to test nutrient delivery, germination and transpired water recovery systems for CTF and Salad Machine are being planned.

SUMMARY

Research in Controlled Ecological Life Support Systems conducted by NASA indicate that plant based systems are feasible candidates for supporting humans in space. Ames Research Center has responsibility for Research and Development, System Integration and Control, and Space Flight Experiment portions of the CELSS program.

Important areas for development of new methods and technologies are biomass production, waste processing, water purification, air revitalization and food processing. For the plant system, the approach has been to identify the flexibility and response time for the food, water and oxygen production, and carbon dioxide consumption processes. Tremendous increases in productivity, compared with terrestrial agriculture, have been realized. Waste processing research emphasizes recycle (transformation) of human wastes, trash and inedible biomass to forms usable as inputs to the plant production system. Efforts to improve efficiency of the plant system, select "new" CELSS crops for a balanced diet, and initiate closed system research with the Crop Growth Research Chambers continue. The System Control and Integration program goal is to insure orchestrated system operation of the biological, physical, and chemical component processors of the CELSS. Space flight studies are planned to verify adequate operation of the system in reduced gravity or microgravity environments. The CELSS program's objective is to provide the technology required to support human life during NASA's future long duration missions.